Ice inventory in highly extincted star forming regions: First results of IceAge, a JWST Early Release Science program

Jennifer Noble, for the IceAge team

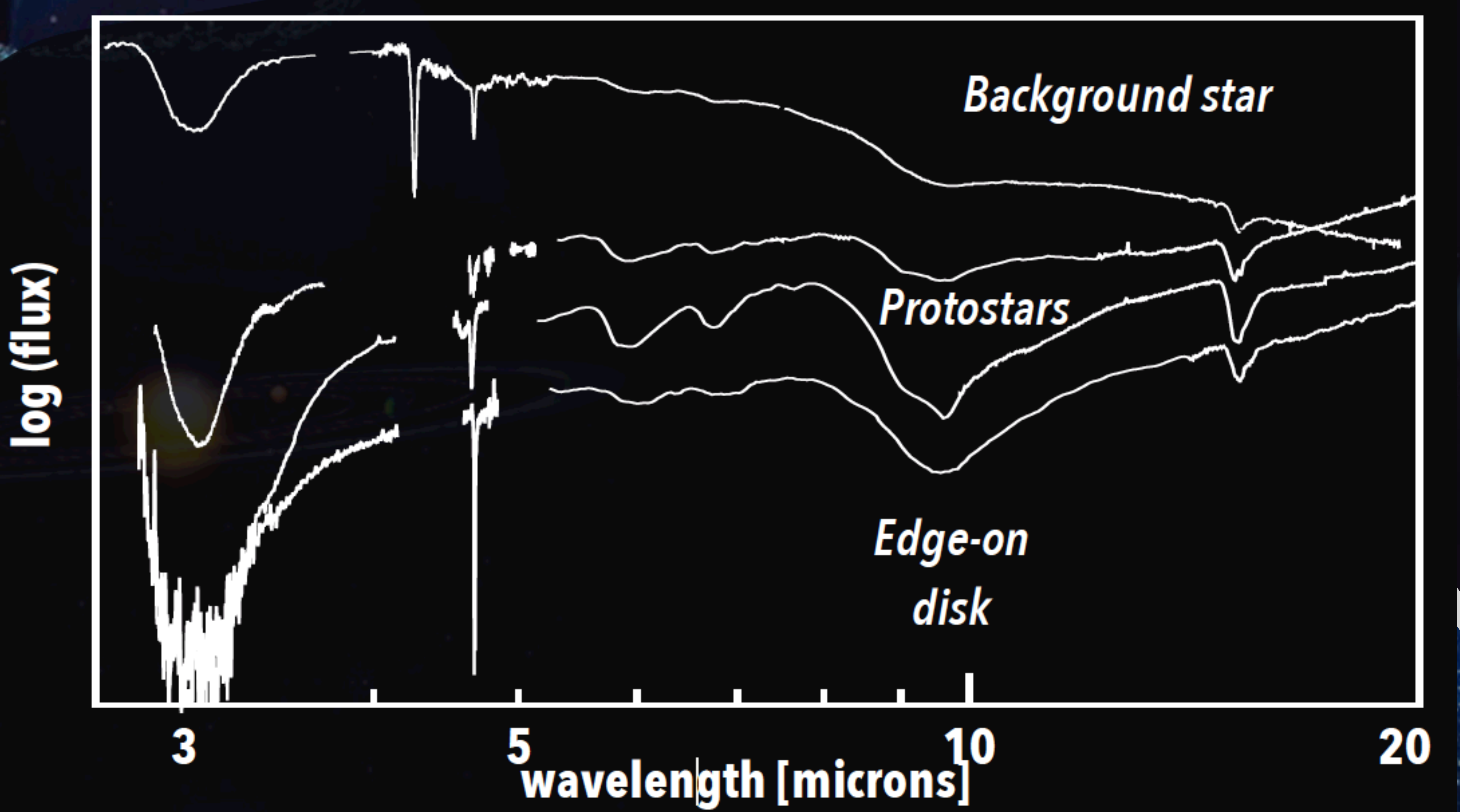
Melissa McClure (PI), Adwin Boogert (co-PI), Harold Linnartz (co-PI)

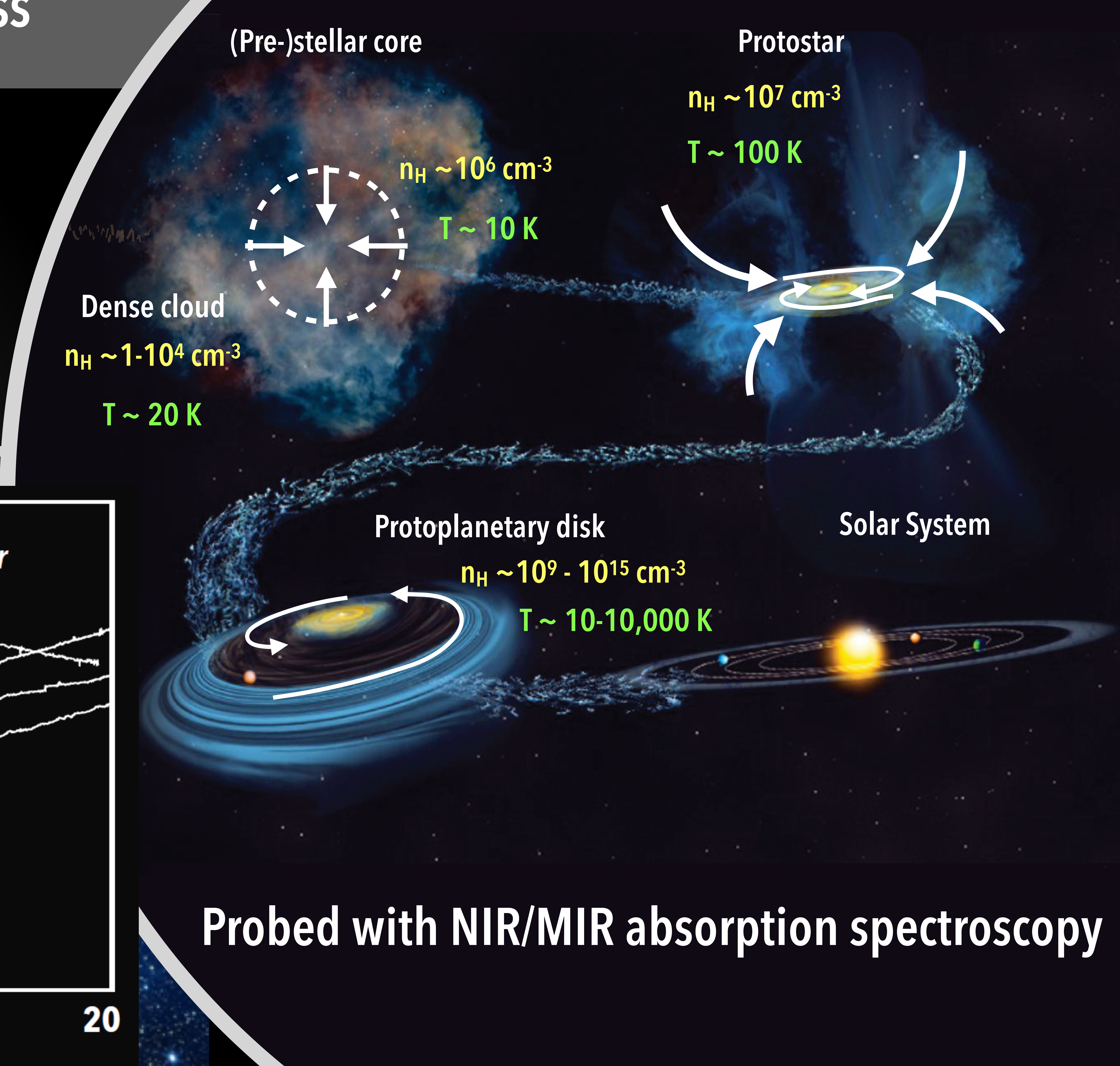
June 20th, 2023
Strasbourg, France

Ices and the star formation process

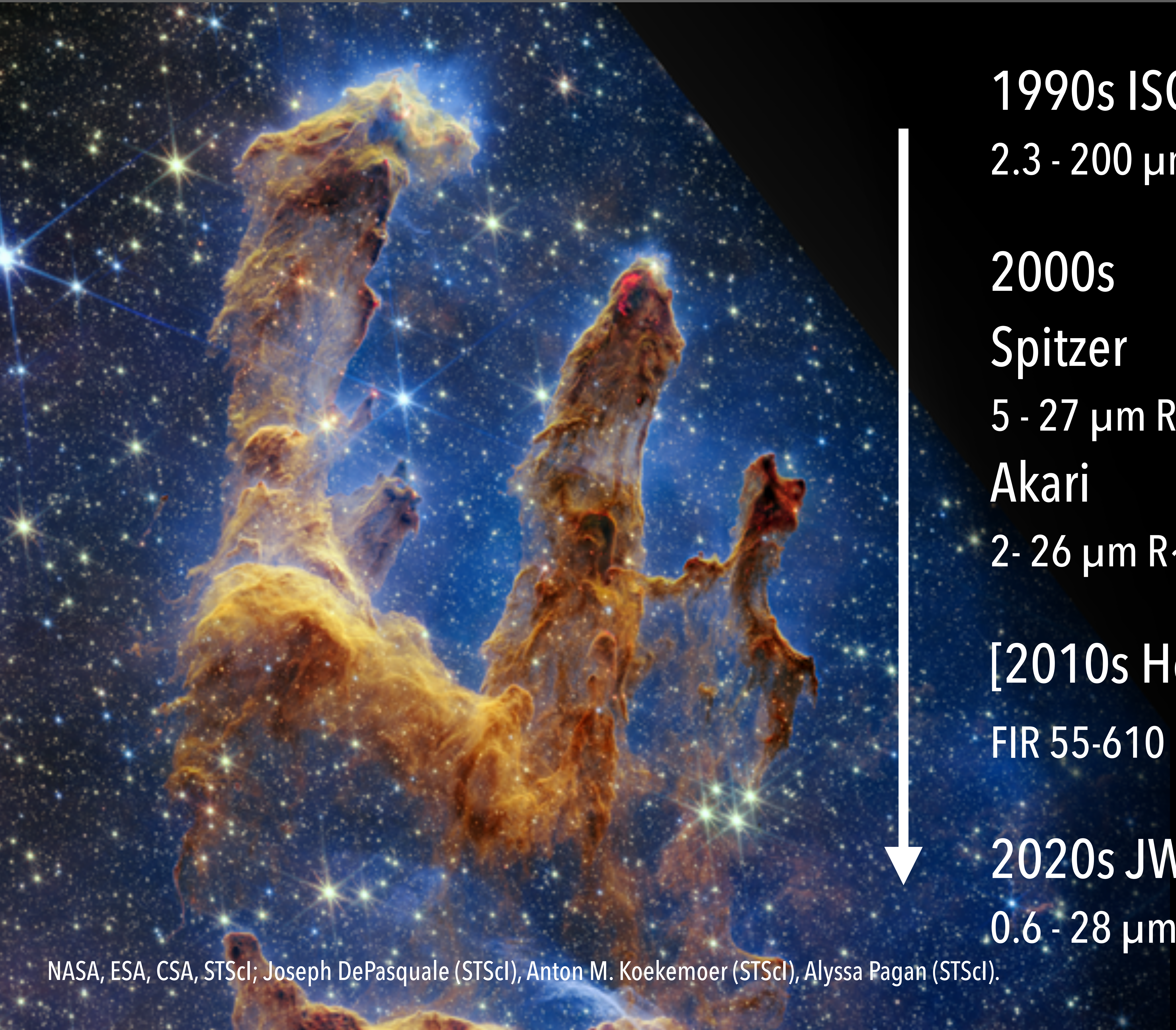
NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Anton M. Koekemoer (STScI), Alyssa Pagan (STScI).
Bill Saxton, NRAO, L. I. Cleeves

Ices and the star formation process





Ices and the star formation process - Observations in the NIR/MIR



1990s ISO

2.3 - 200 μm R < 3000

2000s

Spitzer

5 - 27 μm R~ 60-600

Akari

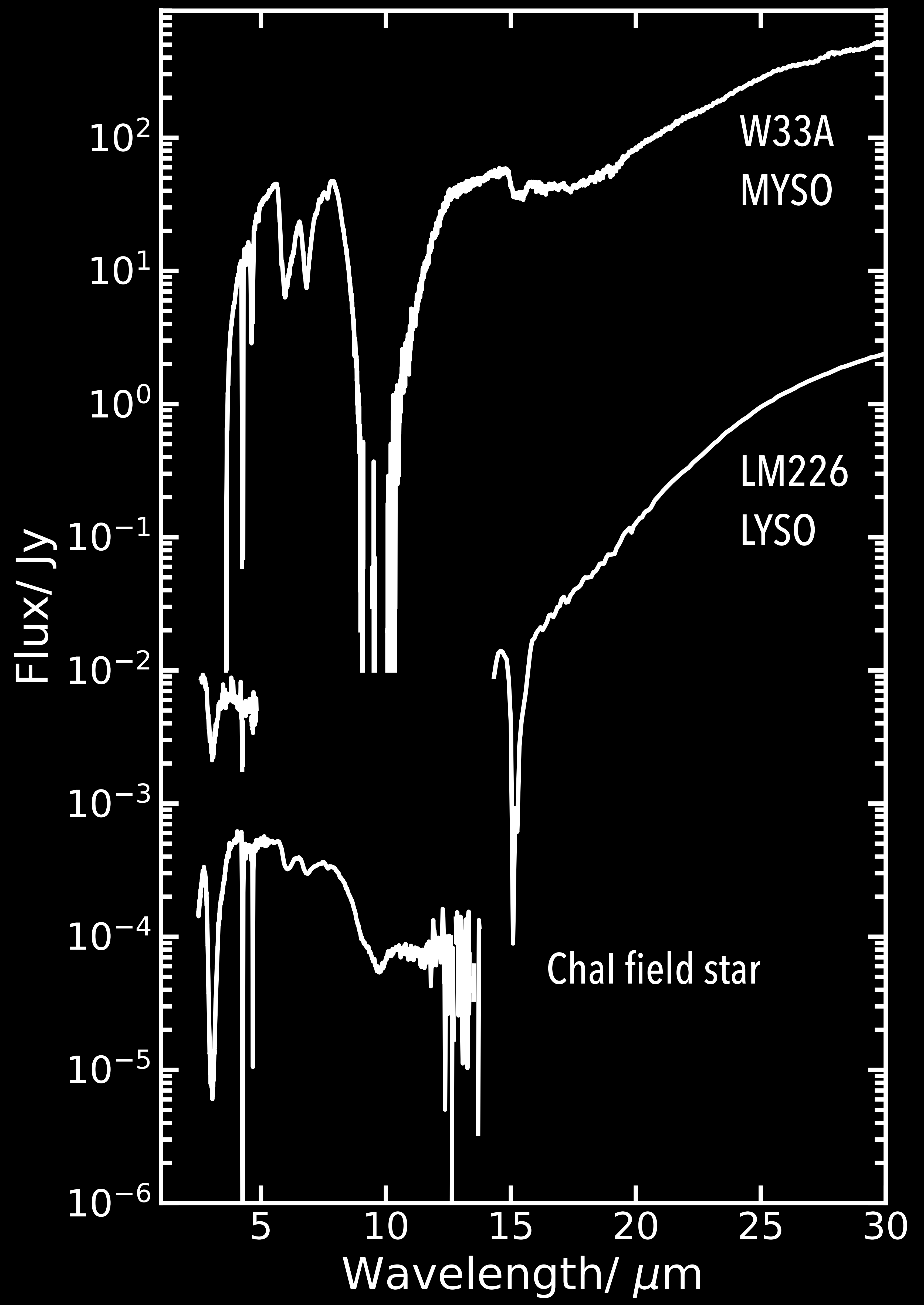
2- 26 μm R~80- 250

[2010s Herschel

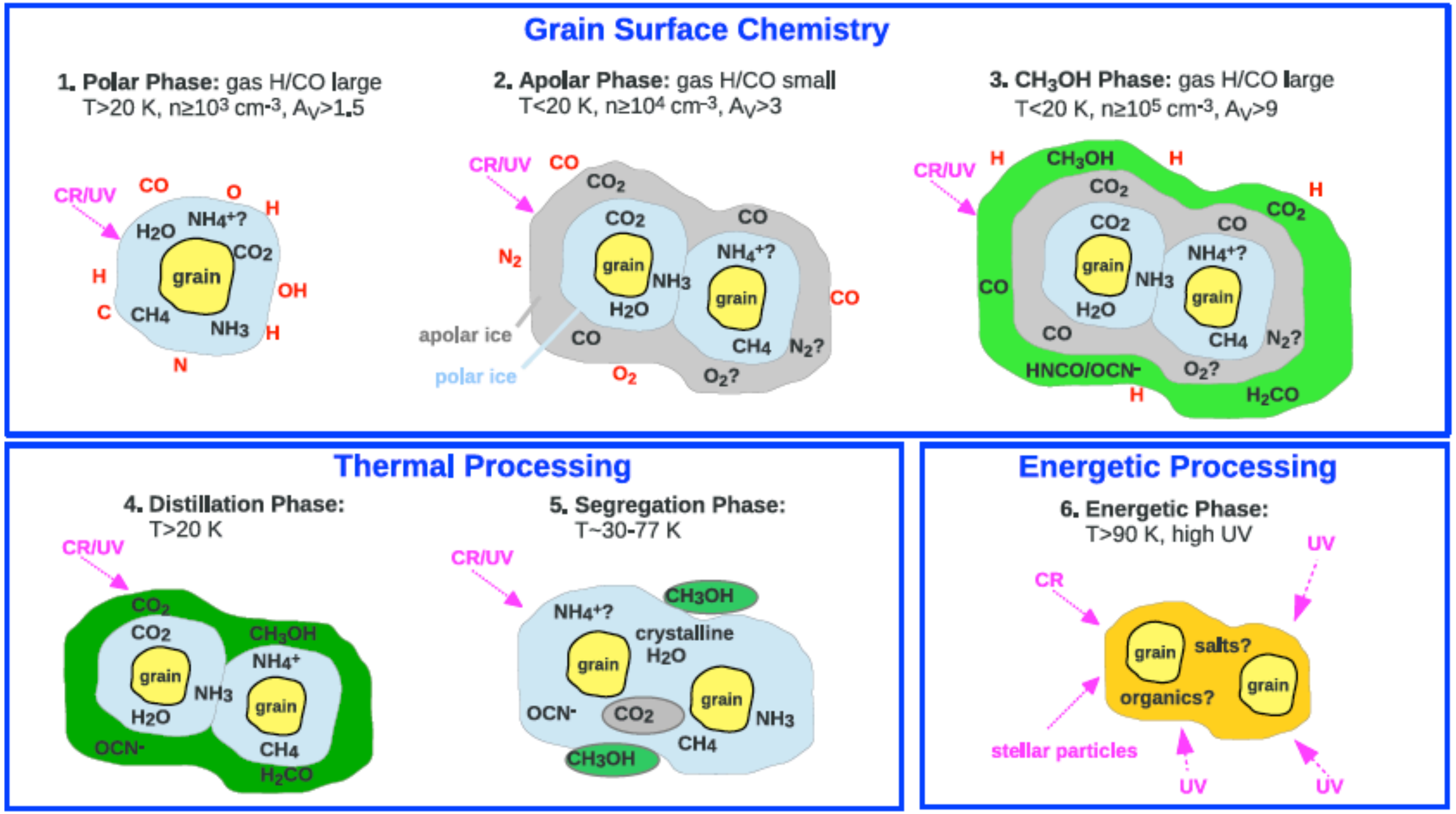
FIR 55-610 μm]

2020s JWST

0.6 - 28 μm R< 3250



Ices and the star formation process - Chemistry and physics of the ice evolution



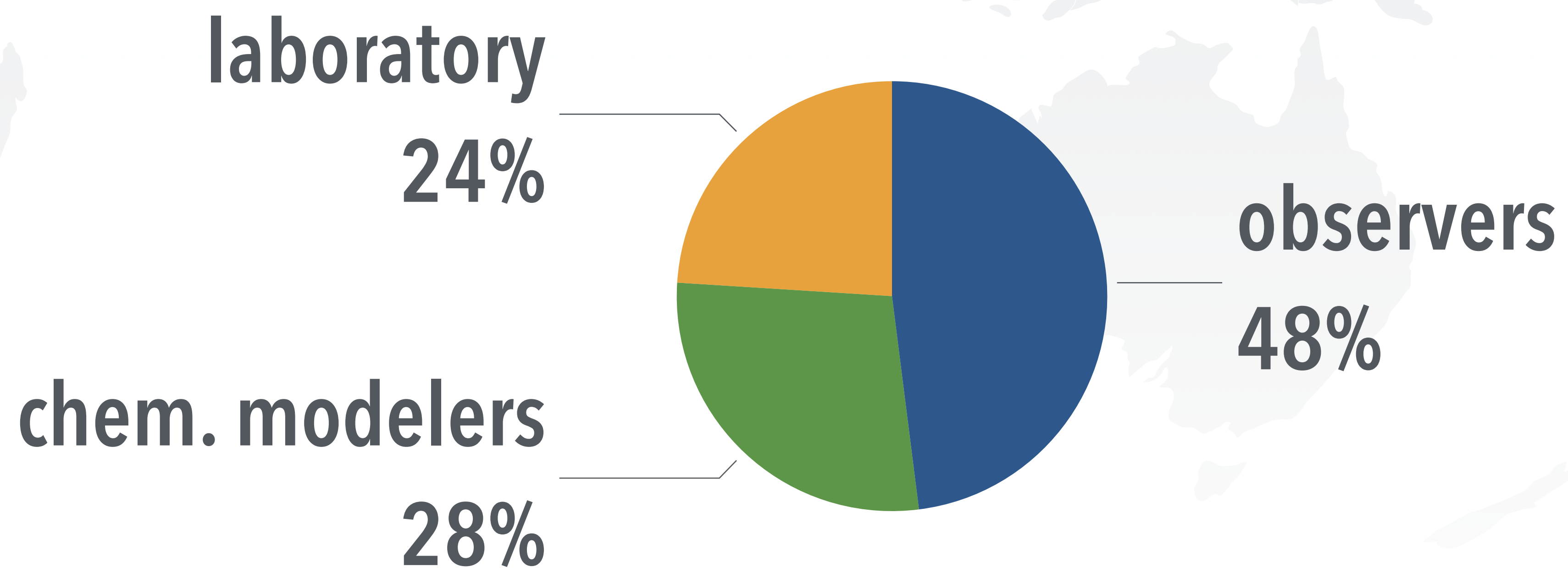
Boogert et al. (2015), ARA&A

JWST IceAge ERS Program

PI McClure (Leiden)

"Early Release Science"

- executed in the *first year of observations* - ***non-proprietary***
- competitively selected (13 of 106 proposals)
- only 1 ERS star formation proposal (PID 1309)
- only cycle 1 proposal spanning cloud to protostar to disk ices



6/51 proposers French

pcmi

JWST IceAge ERS Program target: Chamaeleon I

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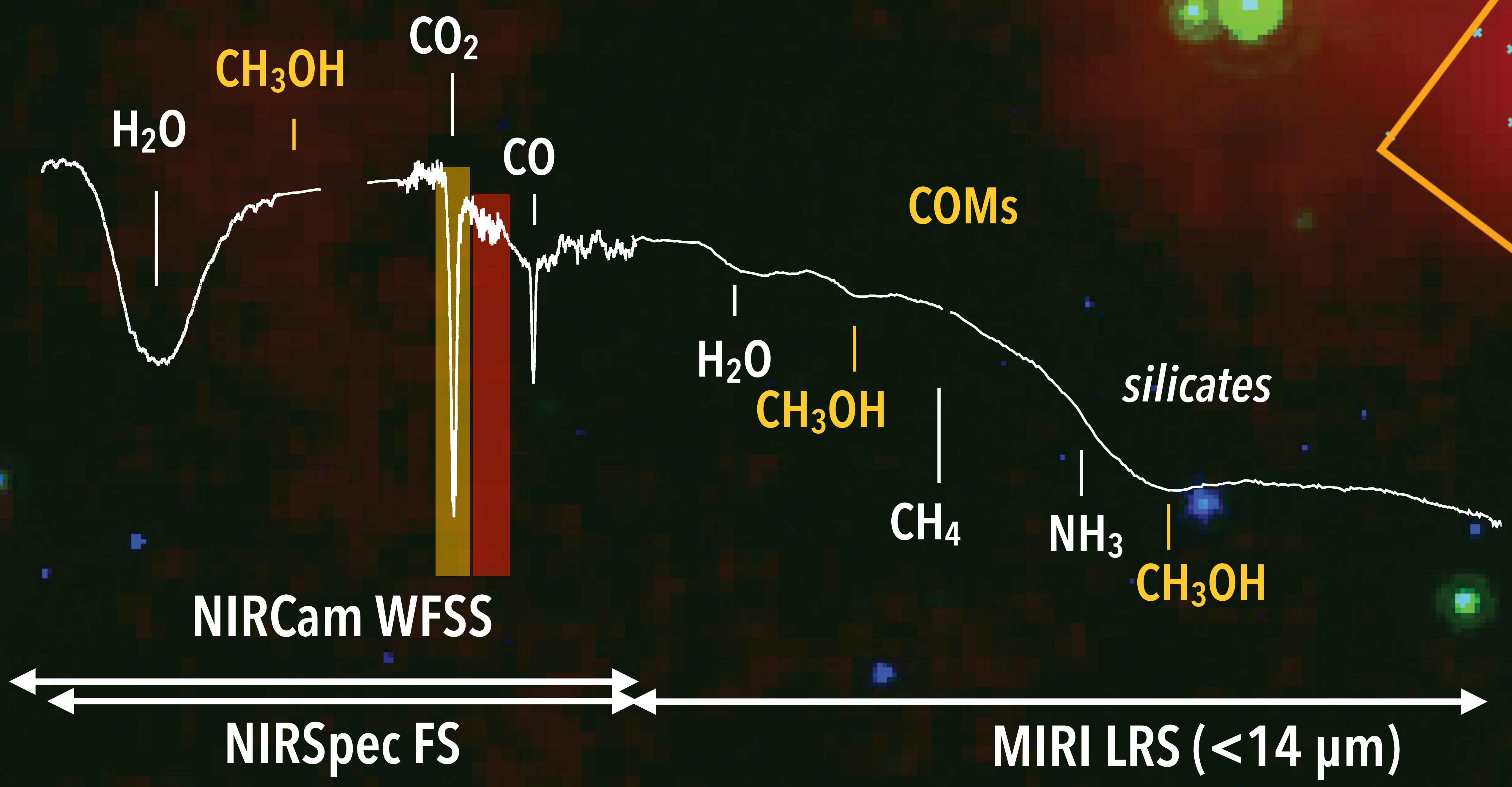
Chamaeleon I, 160 pc: BG stars Persi et al (2001), K. Luhman, priv. comm.

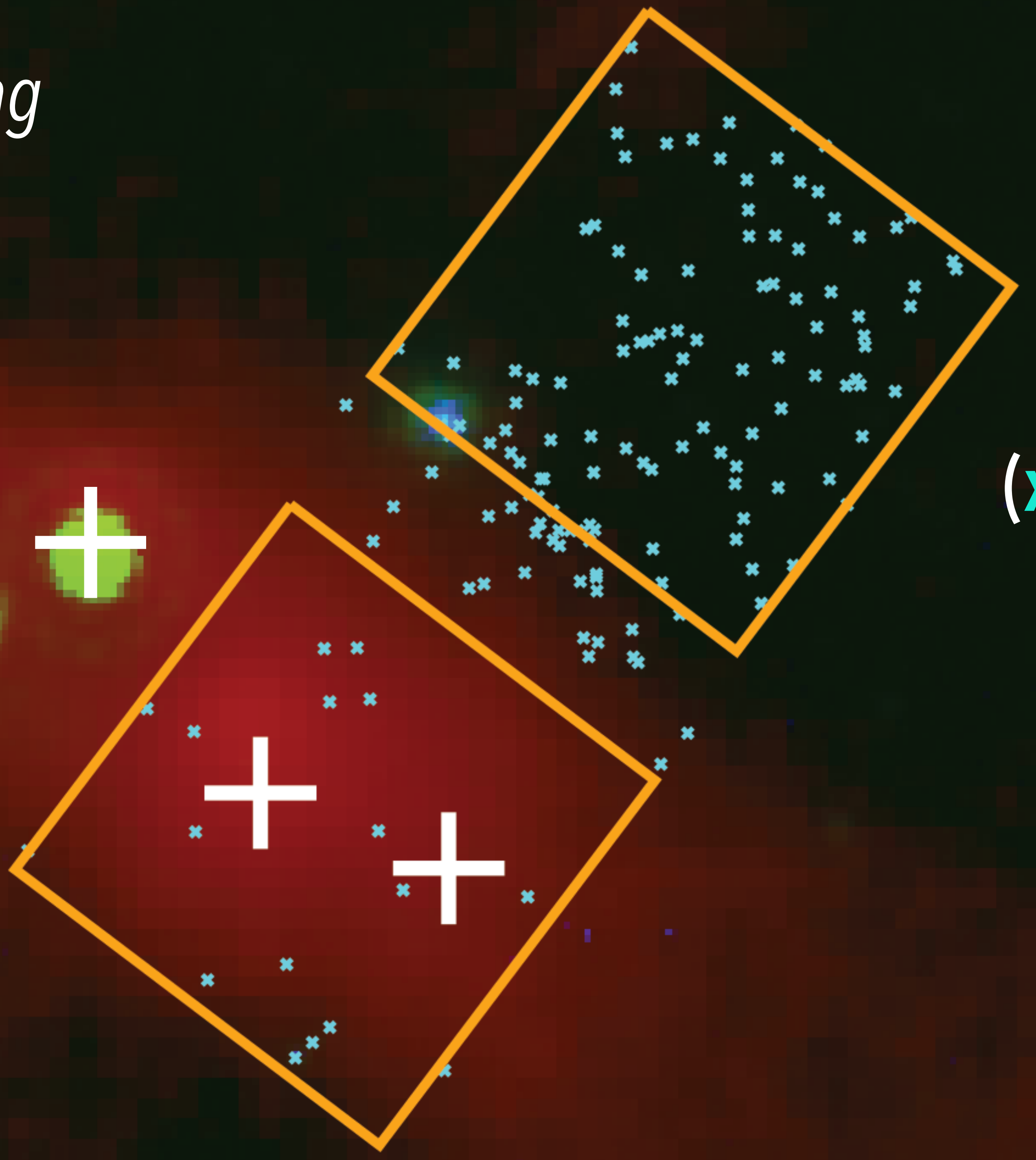
JWST IceAge ERS Program target: Chamaeleon I

1. Demonstrate JWST's ability to map interstellar ices efficiently

- Map 6 main ice species with **NIRCam WFSS**
- 140 background stars, *10x more than previous maps, $A_V \sim 100$ mag*

- Minor ices (OCN-), grain growth/crystallinity in H_2O profile
- Determine Av and extinction law using photospheric features
- Broadband imaging of CO_2



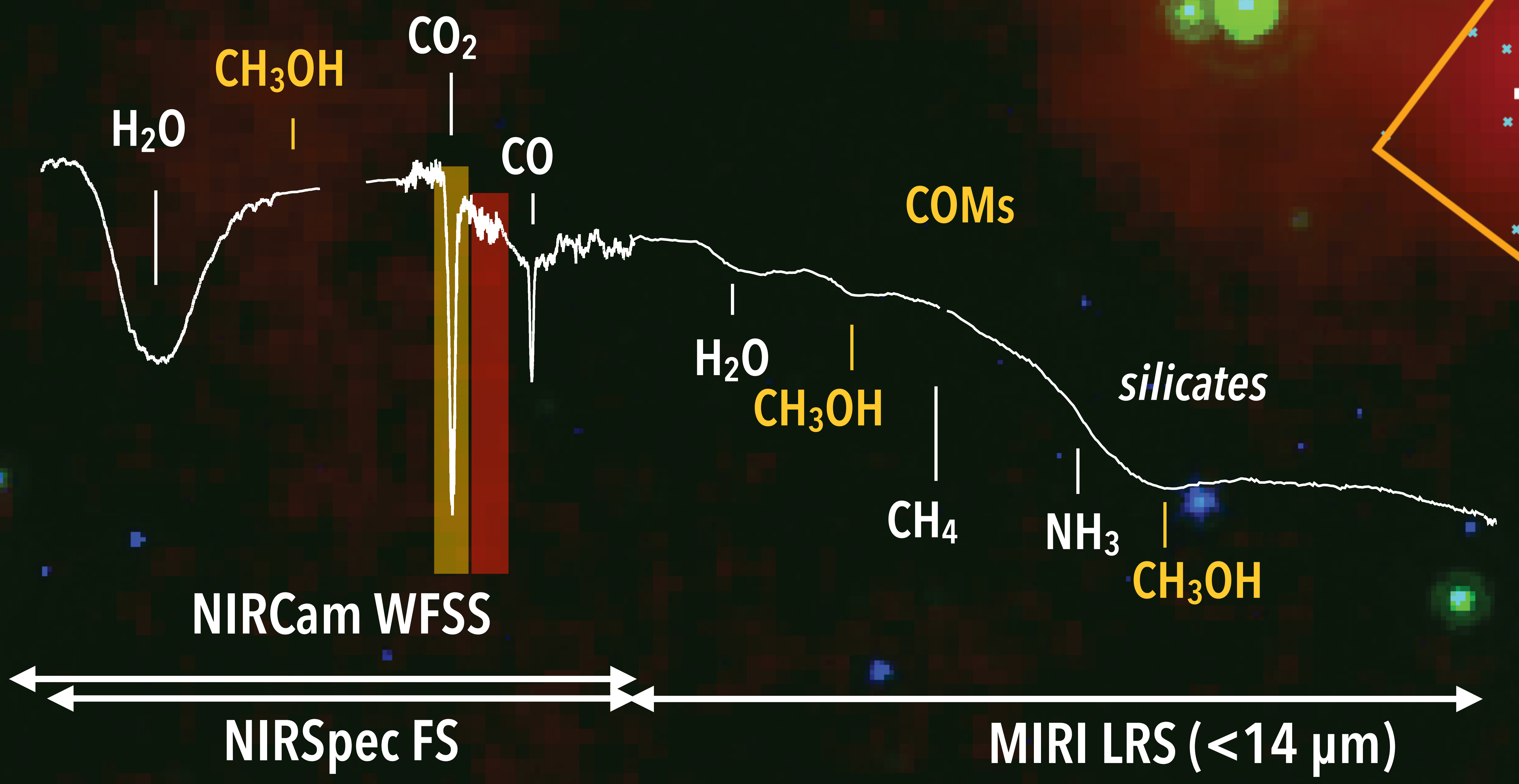


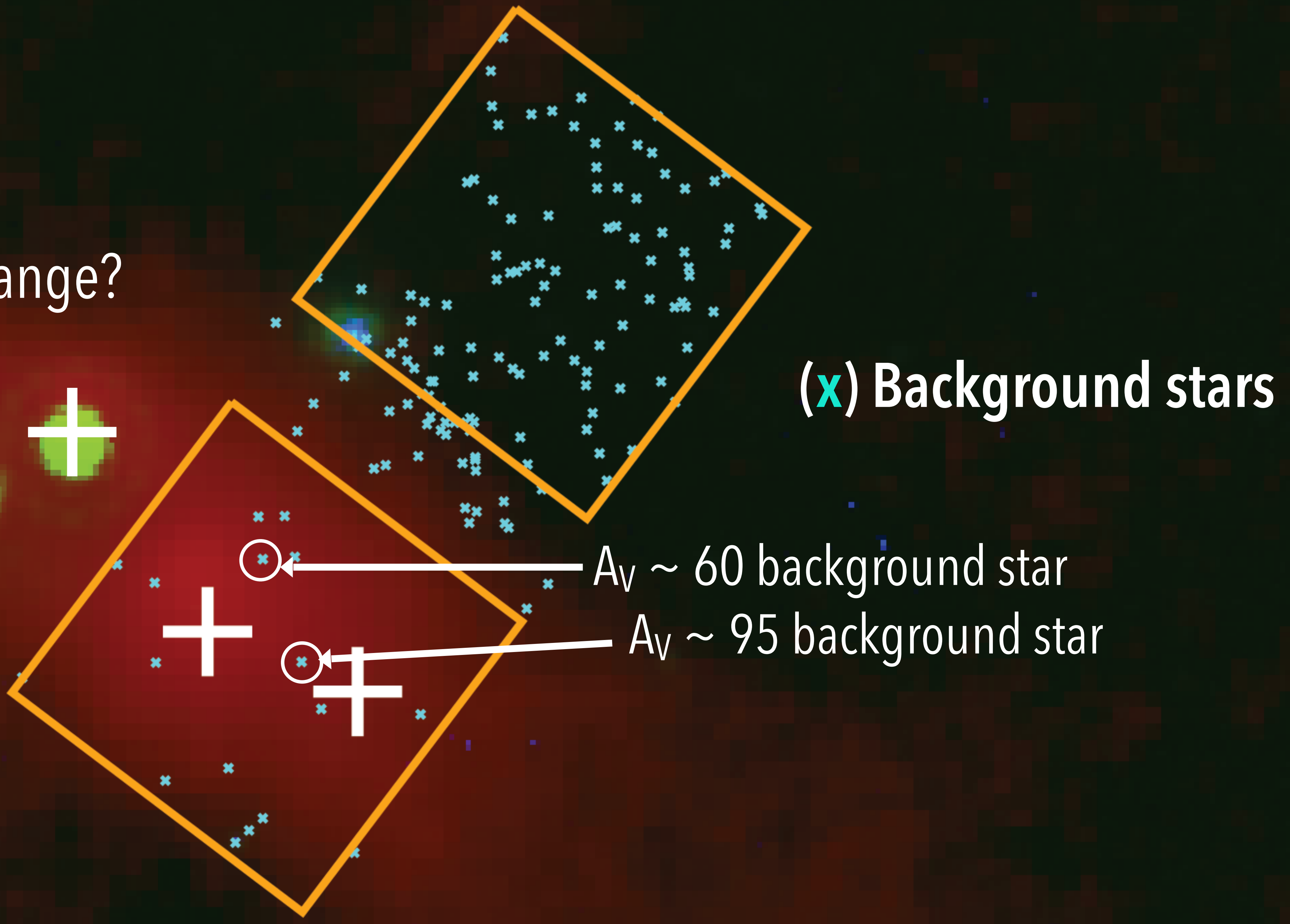
Chamaeleon I, 160 pc: BG stars Persi et al (2001), K. Luhman, priv. comm.

JWST IceAge ERS Program target: Chamaeleon I

2. Explore ice evolution from cold clouds to protoplanetary disks

- Targeted observations of two high-Av background stars with **NIRSpec FS** and **MIRI LRS**
- S/N~300 at 7 microns to measure blended COMs for follow-up
- Deepest ever background star observations; does ice chemistry change?



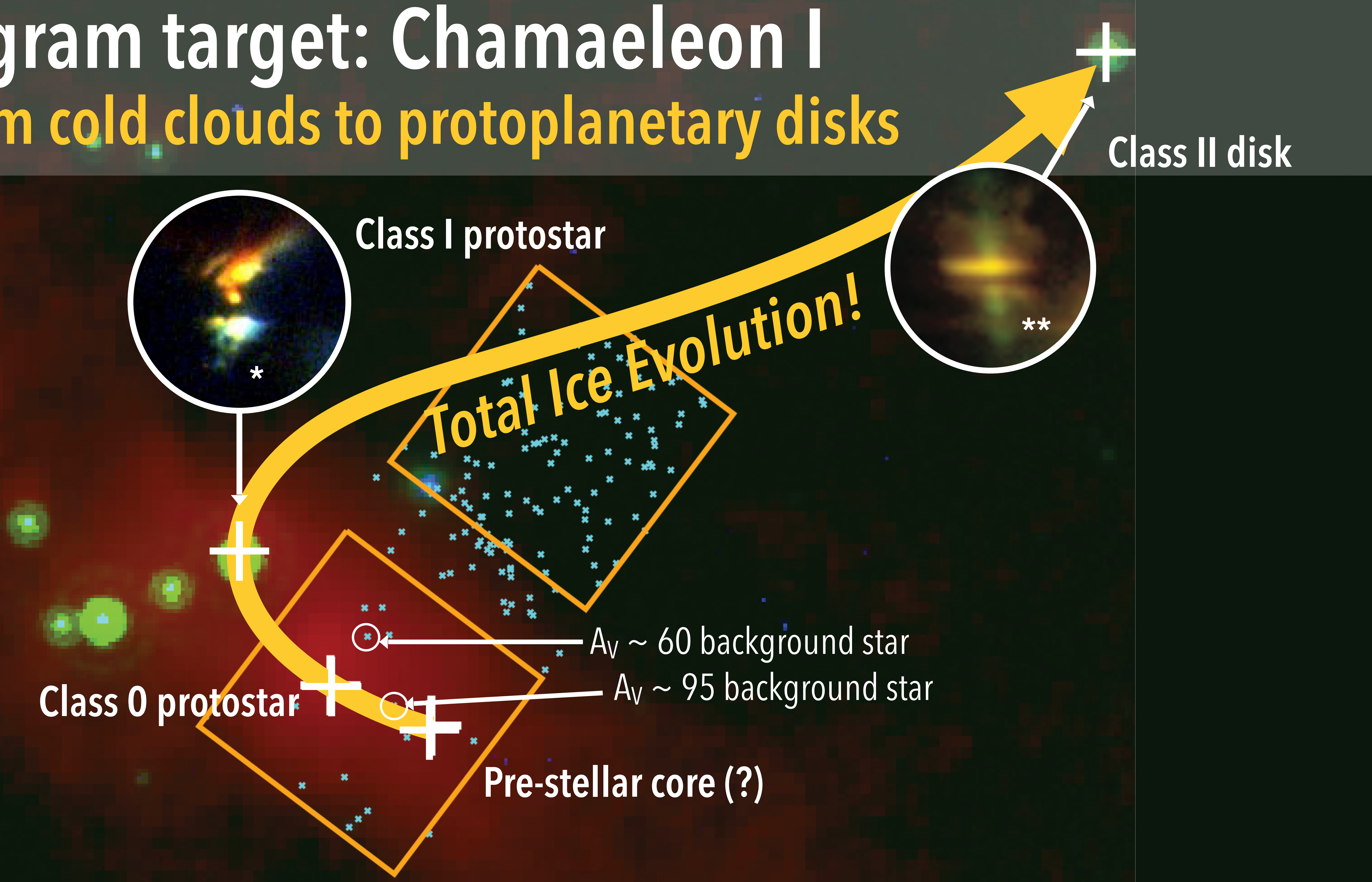


Chamaeleon I, 160 pc: BG stars Persi et al (2001), K. Luhman, priv. comm.

JWST IceAge ERS Program target: Chamaeleon I

2. Explore ice evolution from cold clouds to protoplanetary disks

- Spatial distribution of major ices in extended Class I protostar and Class II disk using **NIRSpec IFU** and **MIRI MRS**
- Map changes in ice processing signatures
- Formation of Complex organic molecules at each evolutionary stage (core, protostar, disk)



IRAC 3.6 μm

MIPS 24 μm

0.85 mm (contours, Beloche+11)

Chamaeleon I, 160 pc: BG stars Persi et al (2001), K. Luhman, priv. comm.

Data quality is fantastic: clean, detailed composites in the imaging

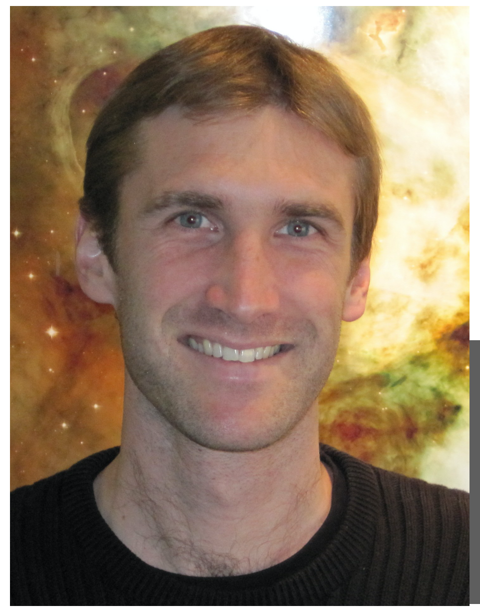
NASA, ESA, CSA, and M. Zamani (ESA/Webb); Science: F. Sun (Steward Observatory), Z. Smith (Open University), and the Ice Age ERS Team. *F150, F200, F410, F430*

Data quality is fantastic, great agreement between instruments!

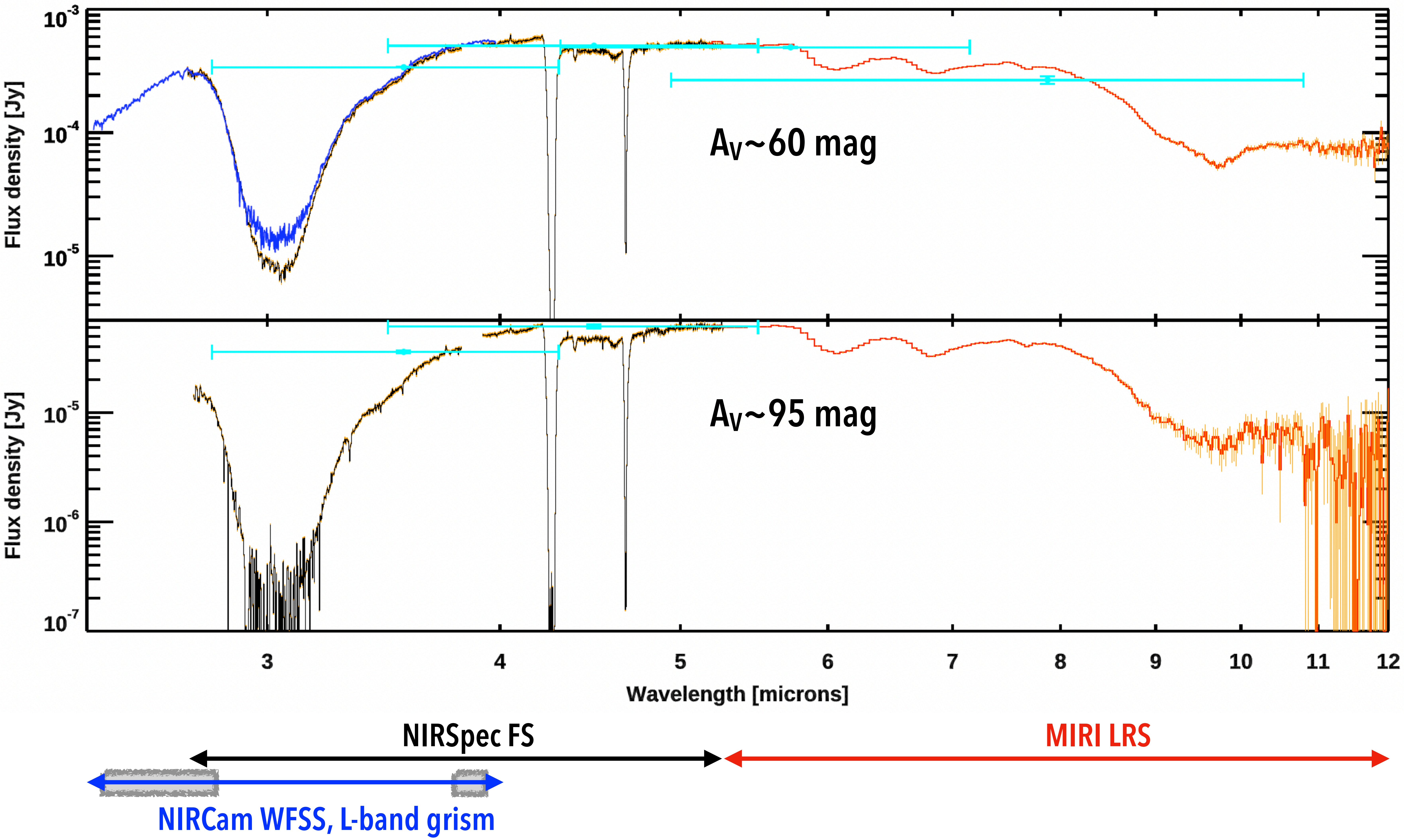
NIRSpec
K. Pontoppidan

NIRCam
Zak Smith

NIRCam
Fengwu Sun



MIRI LRS
Nicolas Crouzet



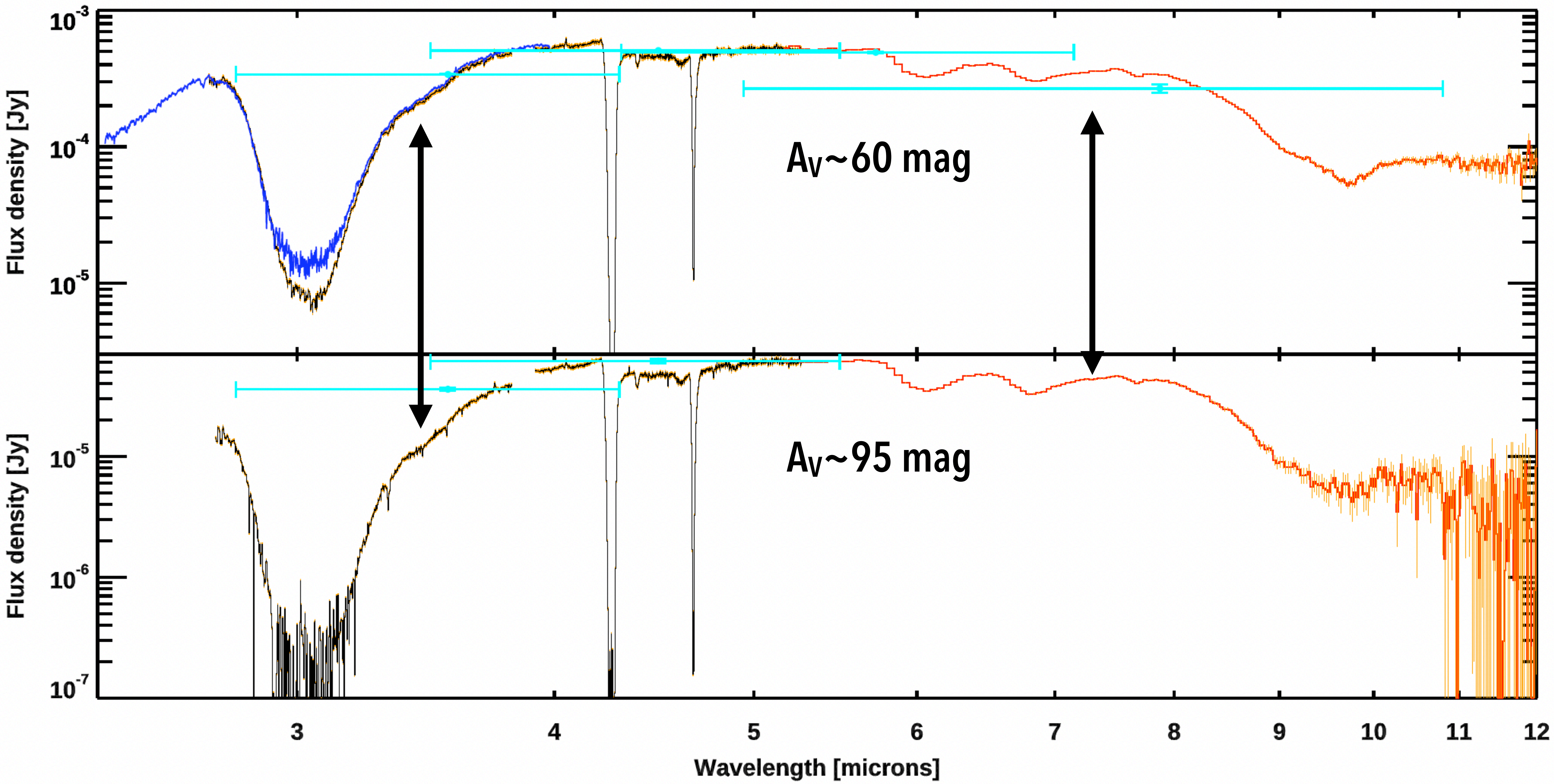
Benchmarking by **T. Beck** (NIRSpec), NIRCam reduction pipeline (**A. Boogert, H. Fraser, E. Egami, NIRCam Team**), wavelength calibration issues **M. McClure/W. Rocha** (MIRI).

Data quality is fantastic, great agreement between instruments!

3σ error bars (orange)

S/N @3.6 µm:
- 210 (A_V~60)
- 150 (A_V~95)

S/N @7.5 µm:
- 455 (A_V~60)
- 165 (A_V~95)



Able to detect 0.2 µJy in wings of A_V ~95 spectrum H_2O feature

Figure 3: McClure + Ice Age Team (2023)

JWST spectra of densest cloud ices to date

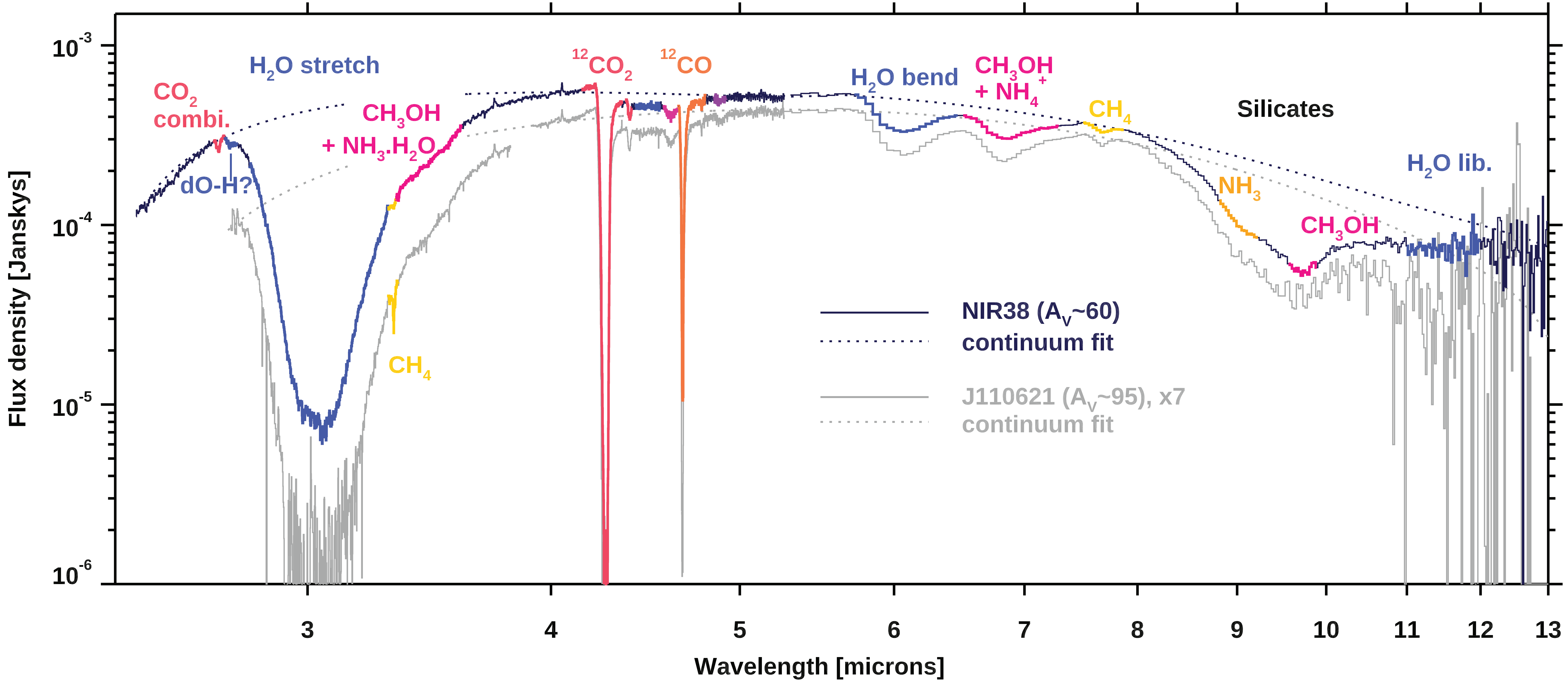
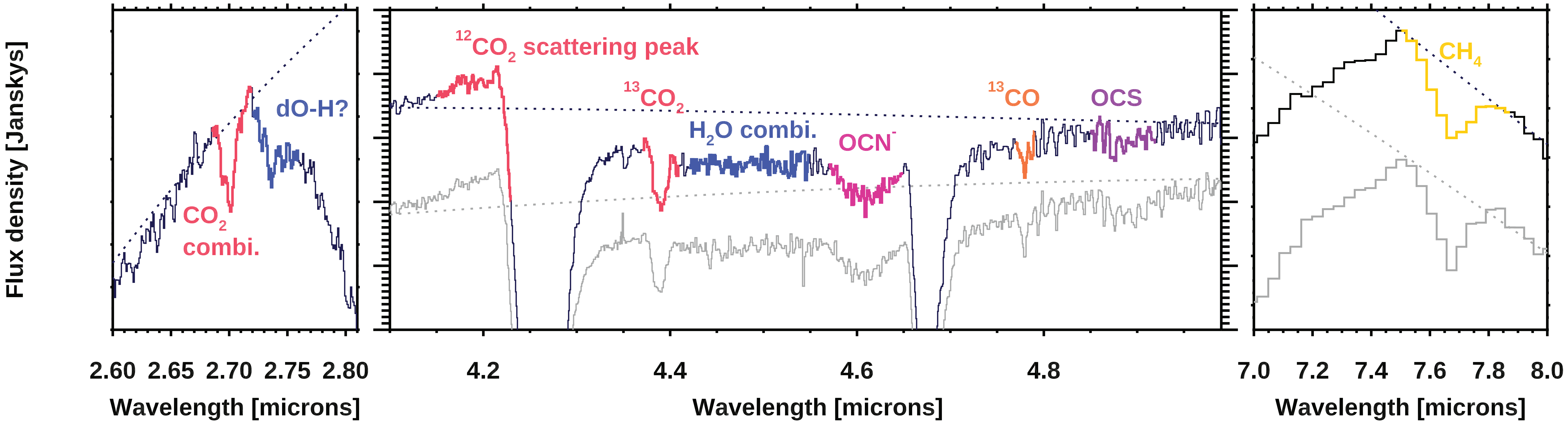


Figure 1: McClure + Ice Age Team (2023)

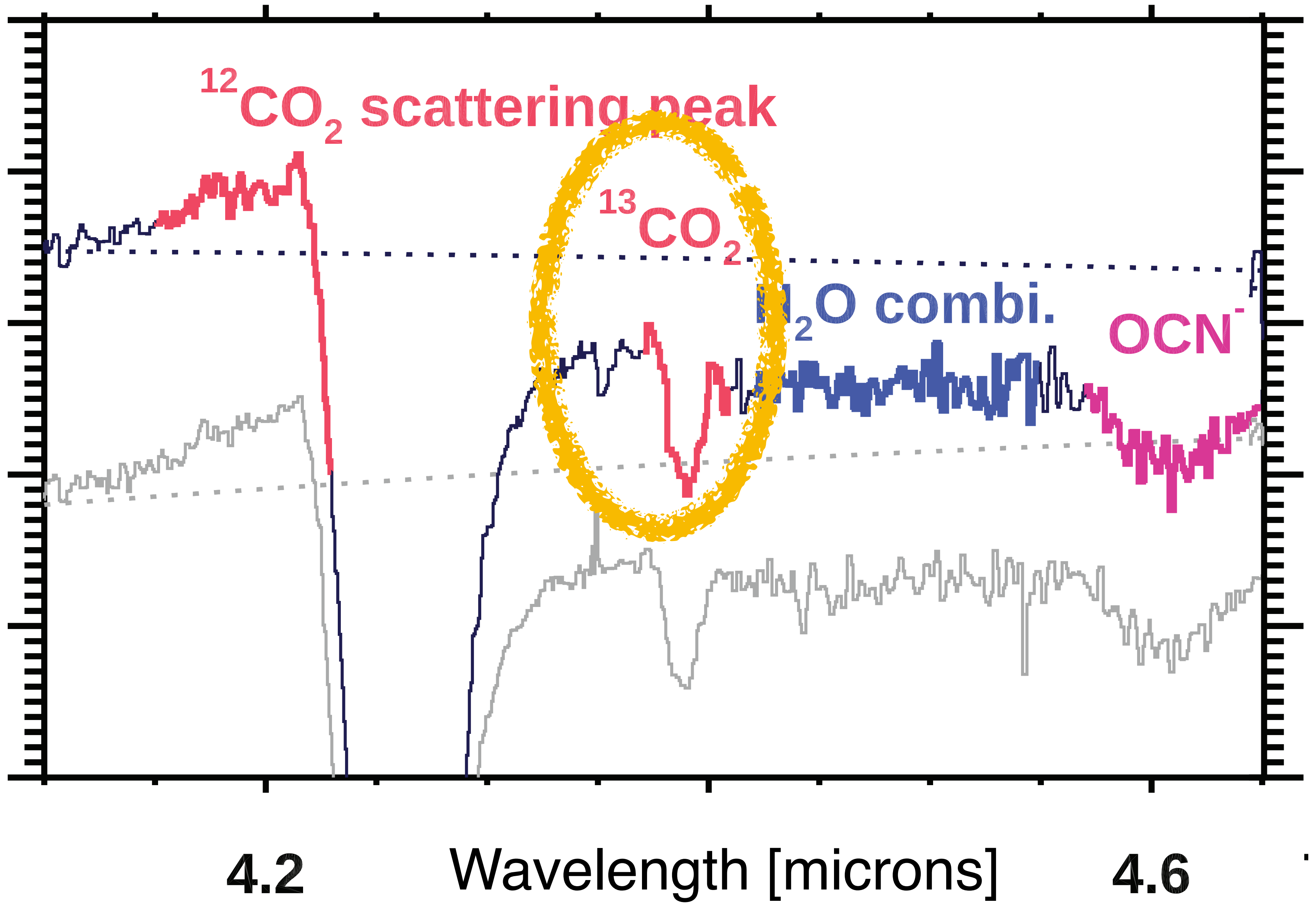
Now easily detect weaker features previously only seen towards brighter protostars



These data allow access to the grain geometry, chemical environment, and elemental budget of cloud ices...

Figure 1: McClure + Ice Age Team (2023)

Signs of grain growth in CO_2 scattering profile



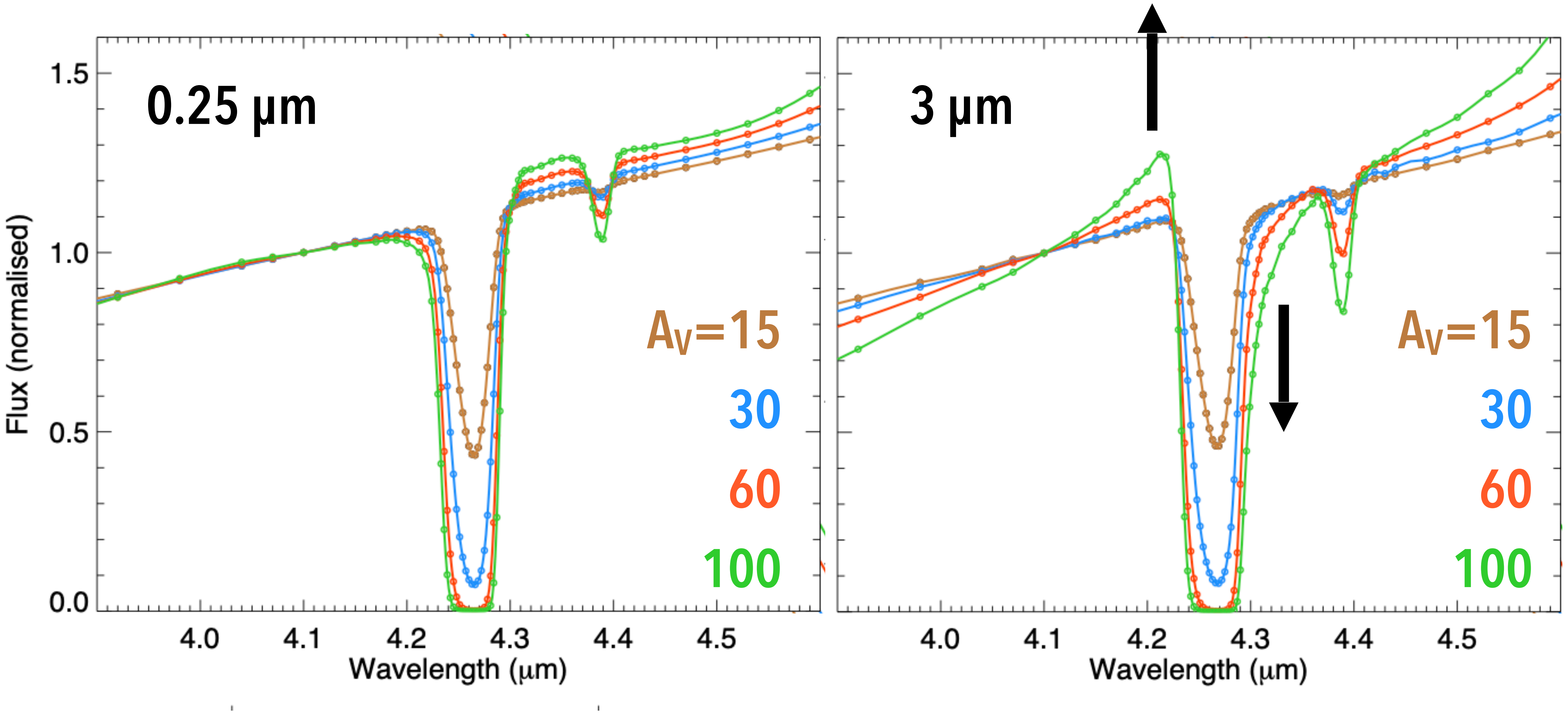


Figure 7: Dartois, Noble et al. (2022)

Icy grain size distribution has a_{max} ~ 1 µm.

Grain growth revealed in H_2O, CO_2 and CO bands.

Radiative Transfer required, even for los in clouds.

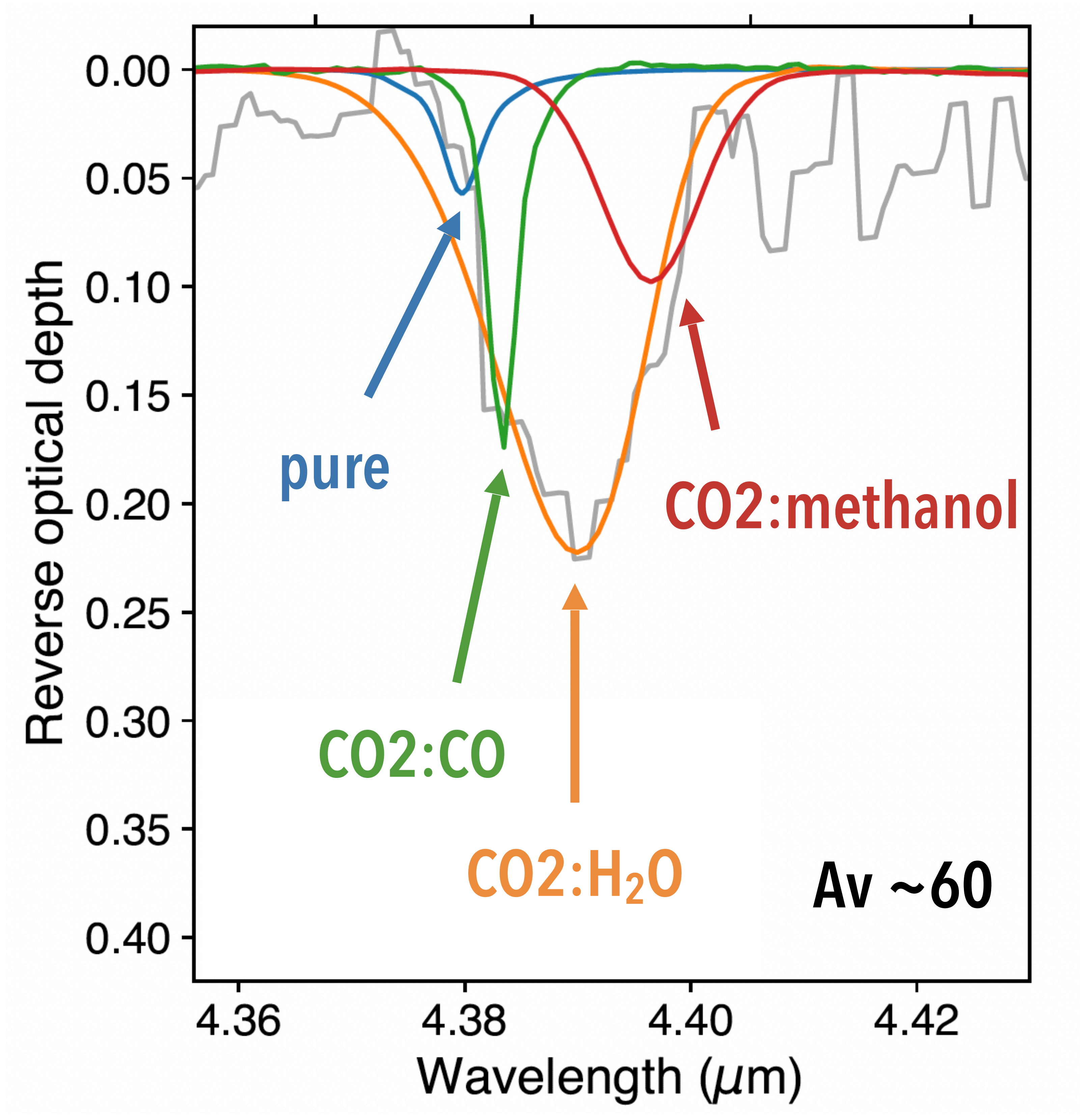
Dartois, Noble, et al. (2023, in prep.)

Analysis
Jenny Noble

Analysis
Emmanuel Dartois

$^{13}CO_2$ in a water-dominated ice environment

$^{12}CO_2$ is saturated ($\tau > 6$), profile lost. Use $^{13}CO_2$ profile to determine local chemical environment in ice.



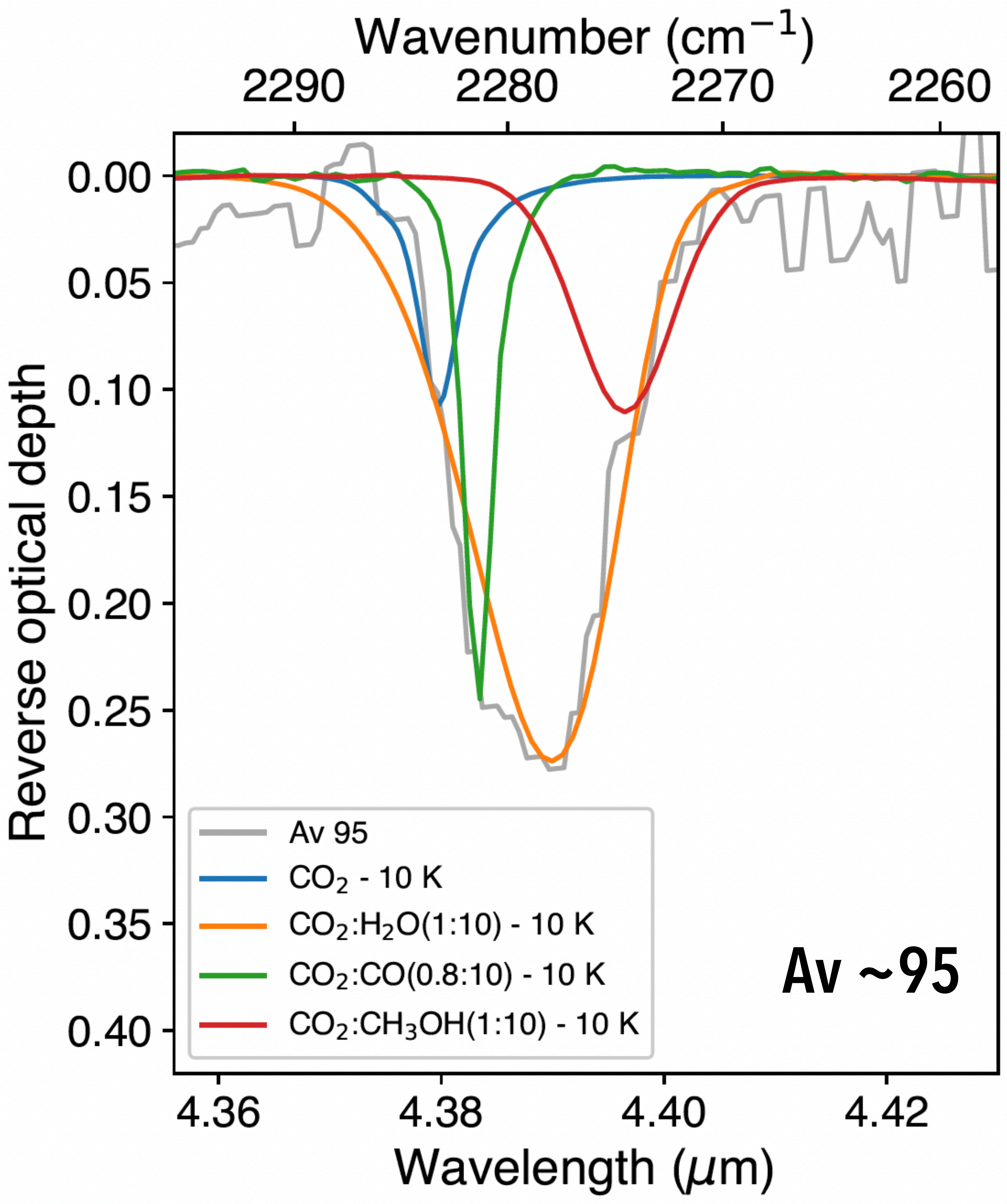


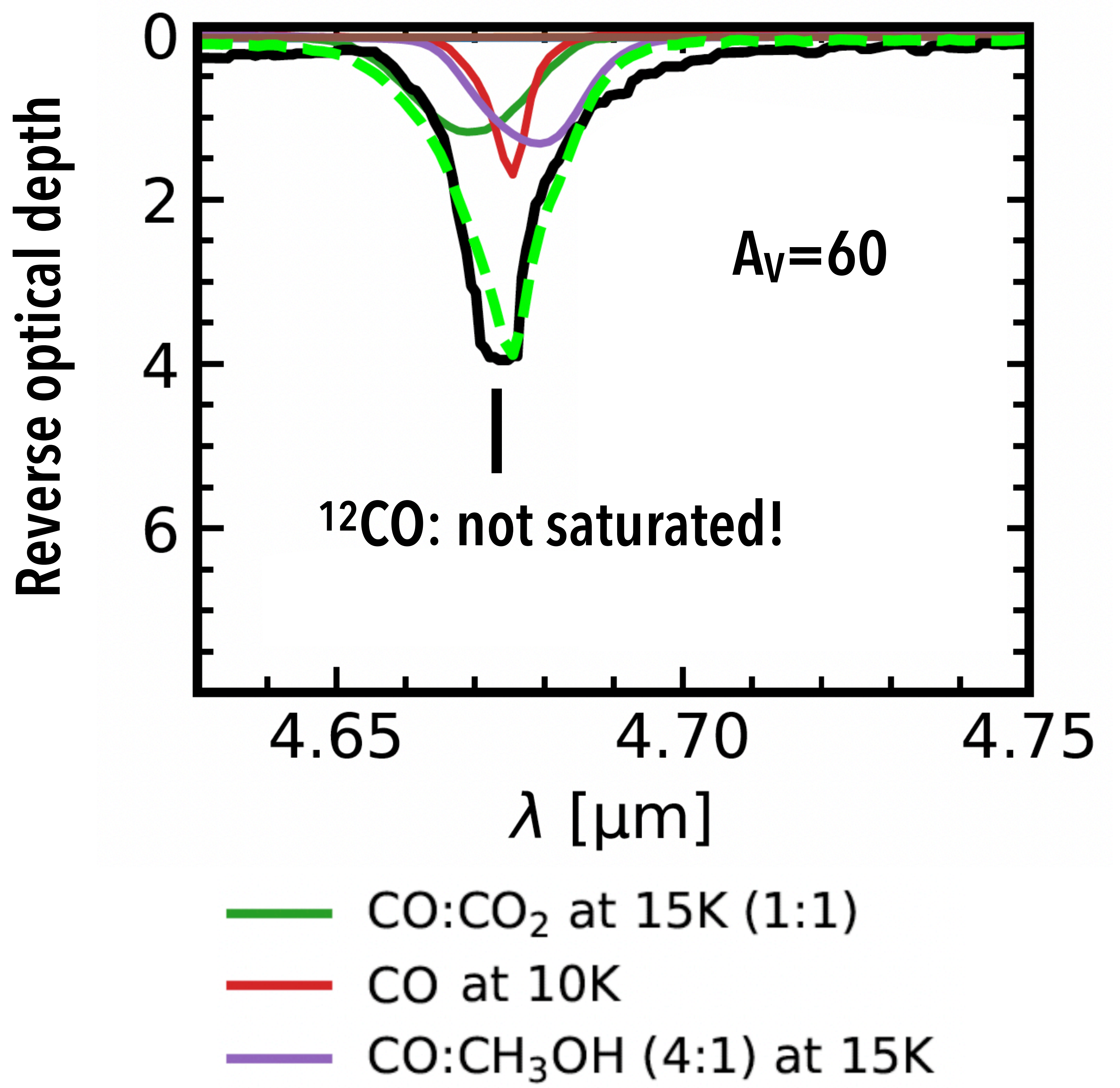
Figure 10: McClure + Ice Age Team (2023)

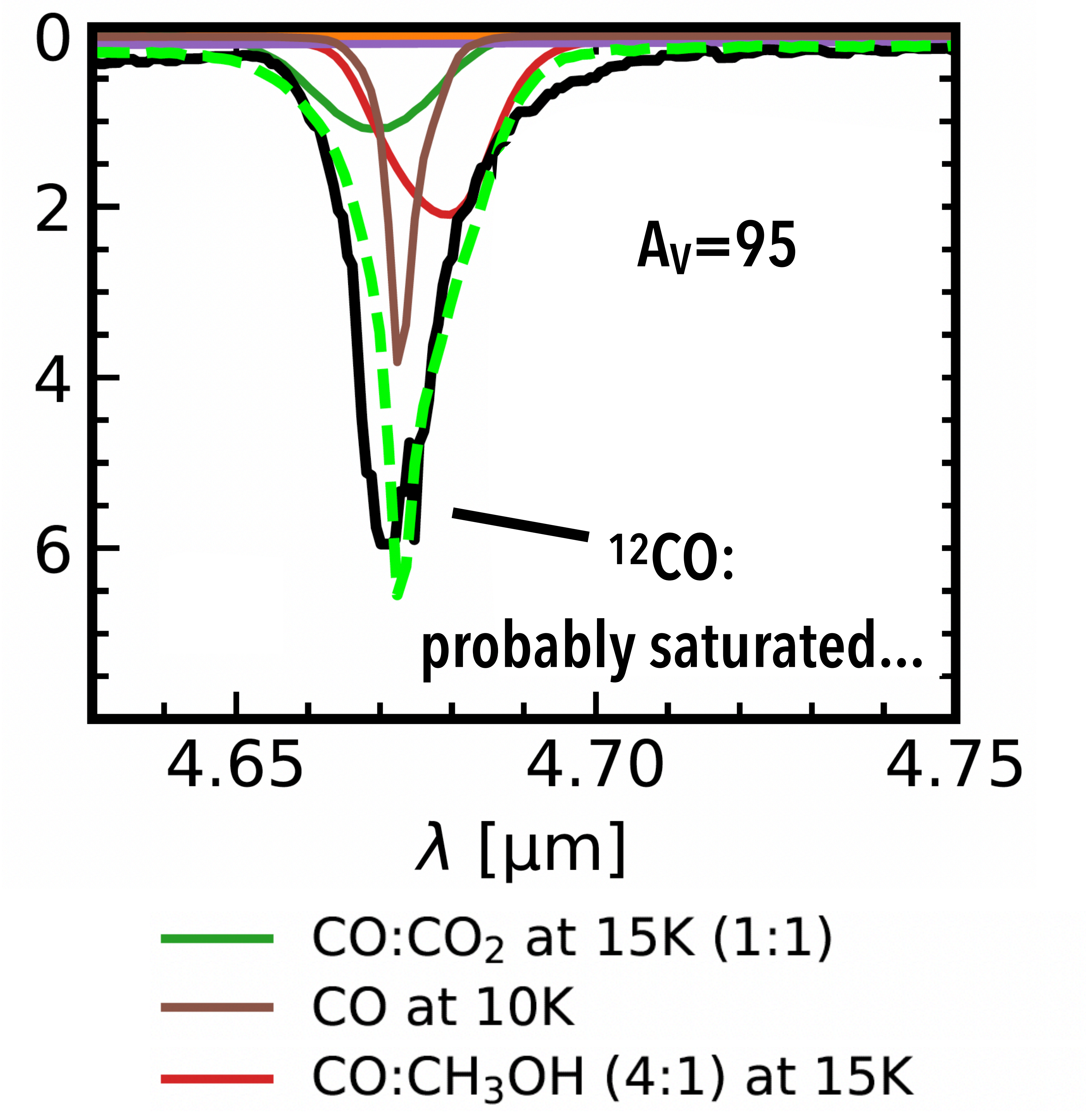
Analysis
Marina Rachid

- CO_2:H_2O (1:10) dominant component
- CO_2:CO (0.8:10) grows with A_V

- Ultimately need grain shape correction
- First Look analysis without

Evidence for ongoing-CO freeze-out: increasingly large pure CO component?





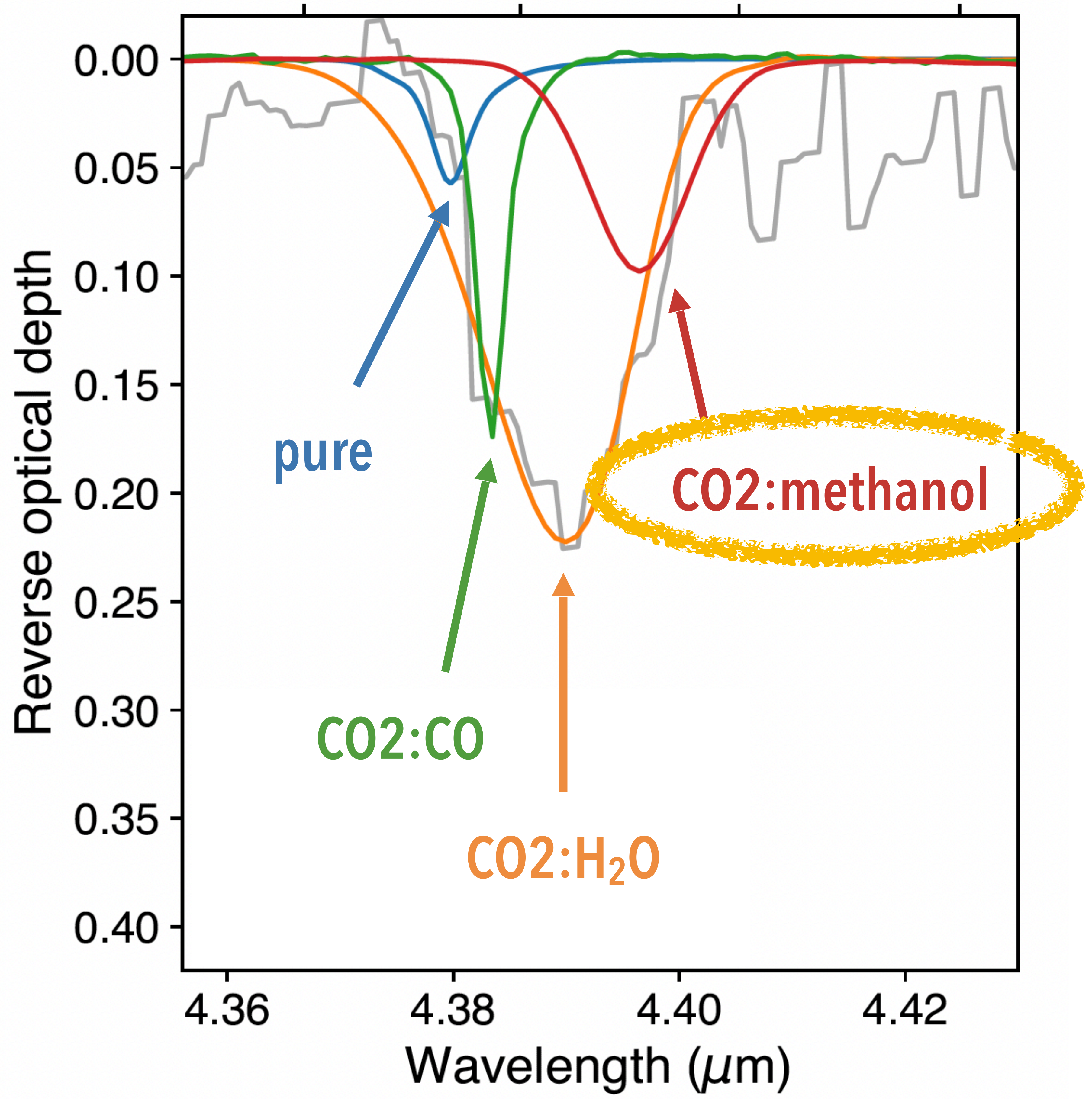
- Gas phase observations will clarify degree of CO freezeout (APEX, Jes Jorgensen)
- Current estimate 45 % (A_V 60) and 33 % (A_V 95) of CO in ice (Herschel)

Figure 5, 6: McClure + Ice Age Team (2023), Pontoppidan et al. (2003-2005)

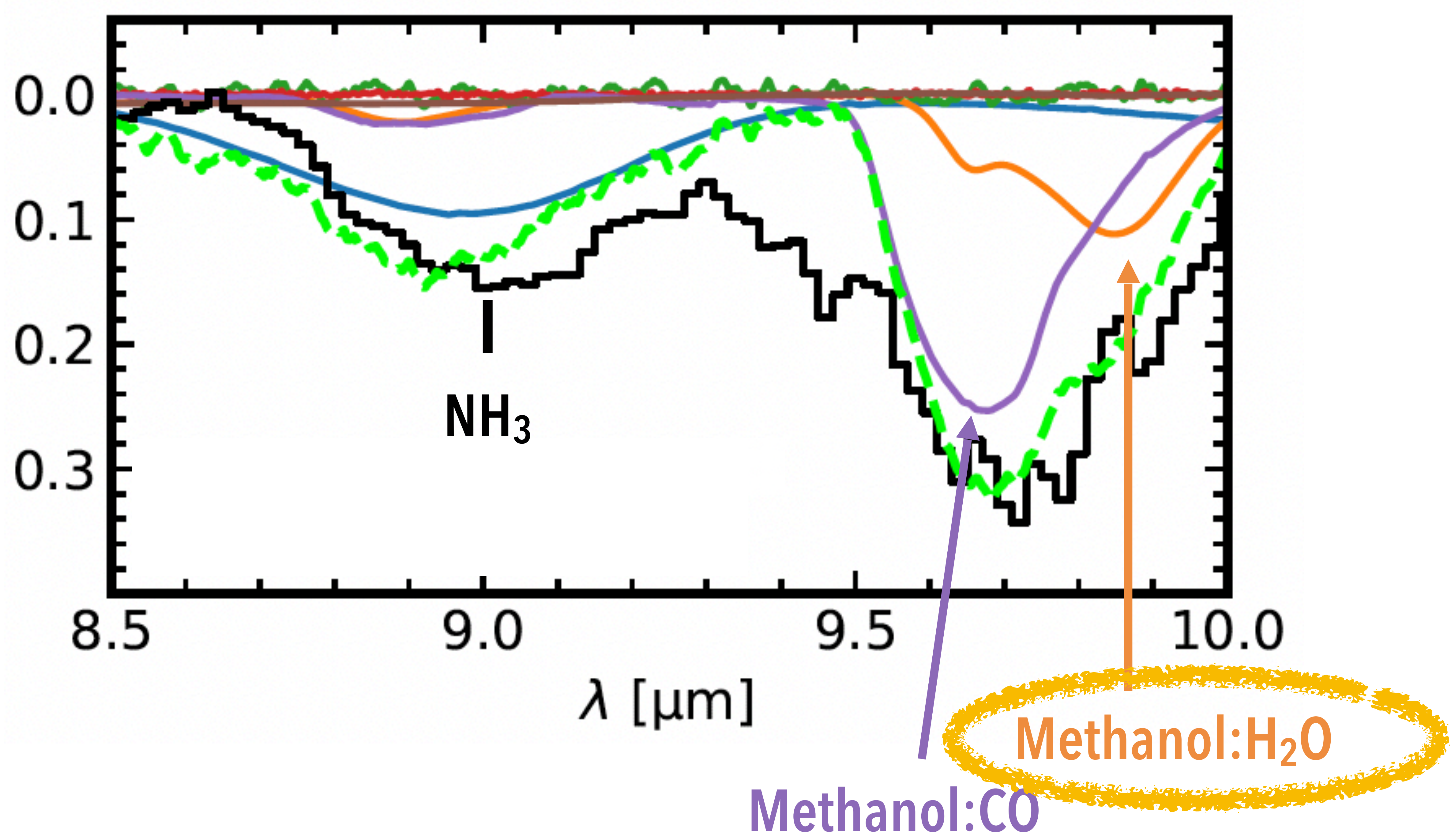
Analysis
Will Rocha

Organic ices form early in a water-dominated ice environment.

$^{13}CO_2$ main feature



CH_3OH (methanol)



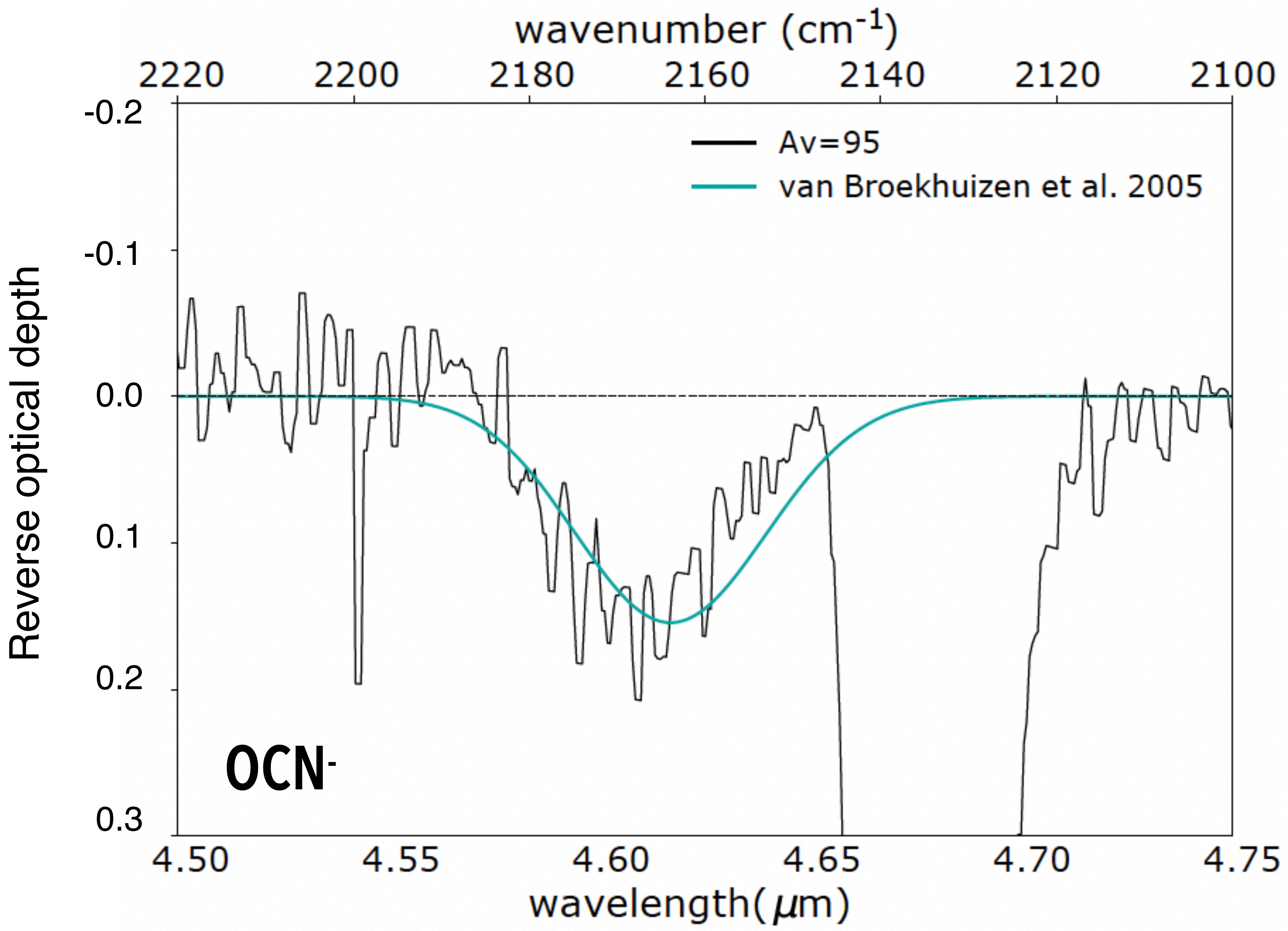
CO_2 and methanol formed ***early*** in water ice matrix.

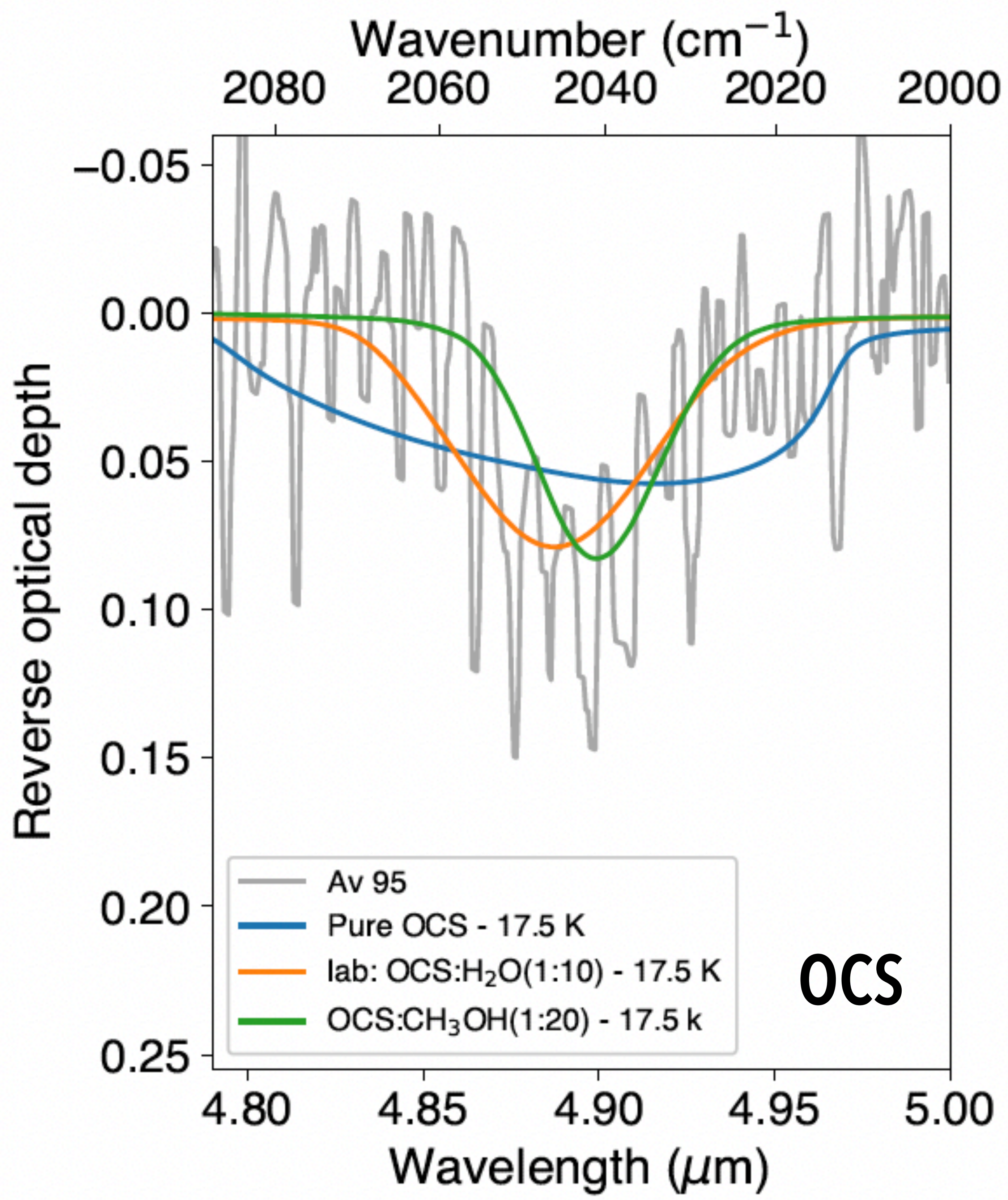
Discussion
Danna Qasim

Discussion
Thanja Lamberts

Figures 5, 10: McClure + Ice Age team (2023), analysis by Dr. Marina Rachid, Dr. Will Rocha

Rich sample of simple inorganic ices now detected





OCN- first detection in cloud

No HCN <0.7-2% H_2O
(similar to 0.1-1% values in comets)

Marina Rachid

Giulia Perotti

OCS first S-bearing molecule
No H_2S <0.6% H_2O
(similar to 1% in comets)

Figures 11, 12, 13: McClure + Ice Age Team (2023)

Ice column densities similar from $20<A_V<95$ magnitudes

- Global column densities (via ENIIGMA code)
- Compare with Elias 16 (A_V~19 mag)
- Generally more ice as A_V increases, but within uncertainties

Relative ice abundances do NOT show a significant dependence on A_V

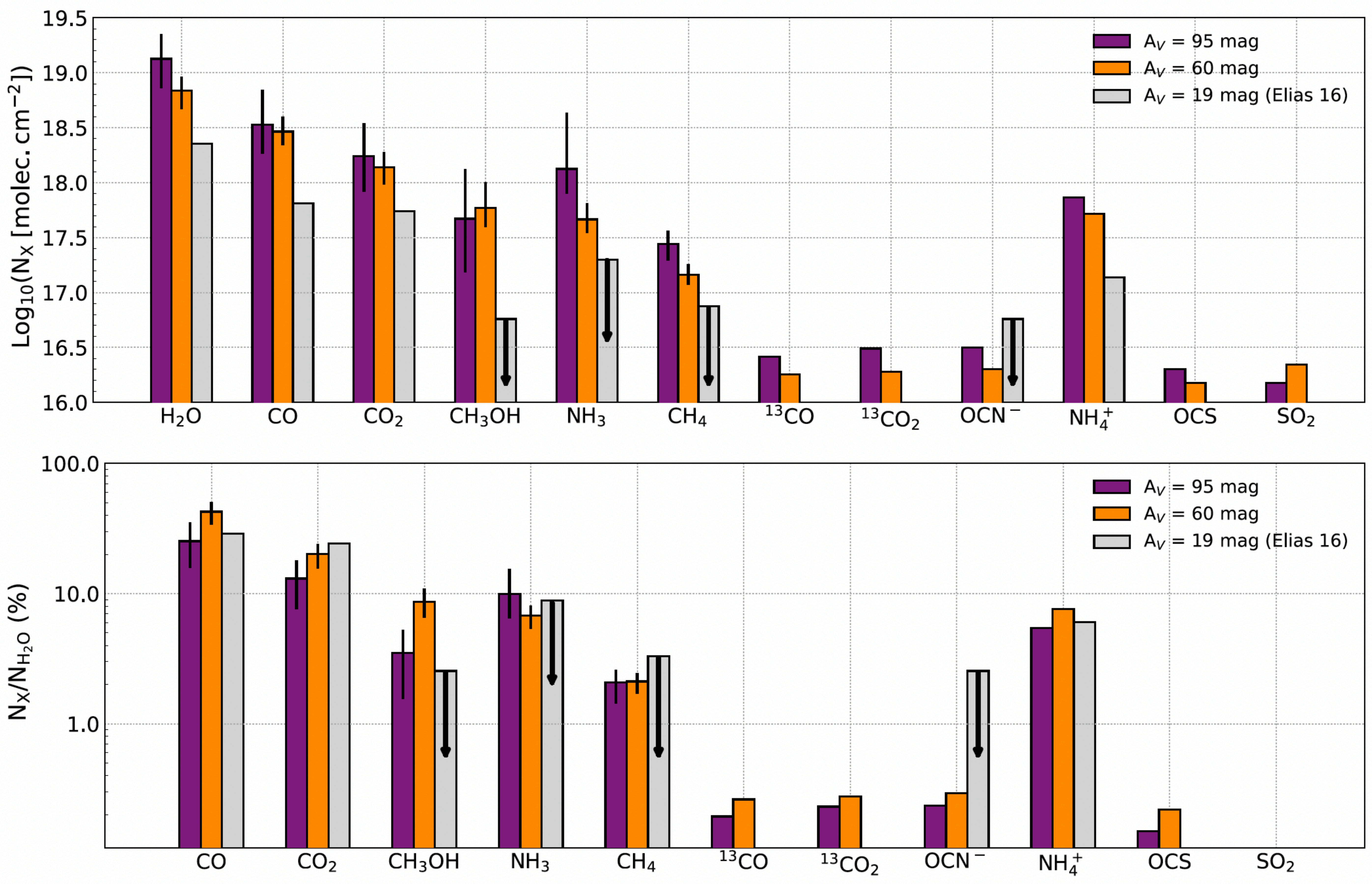


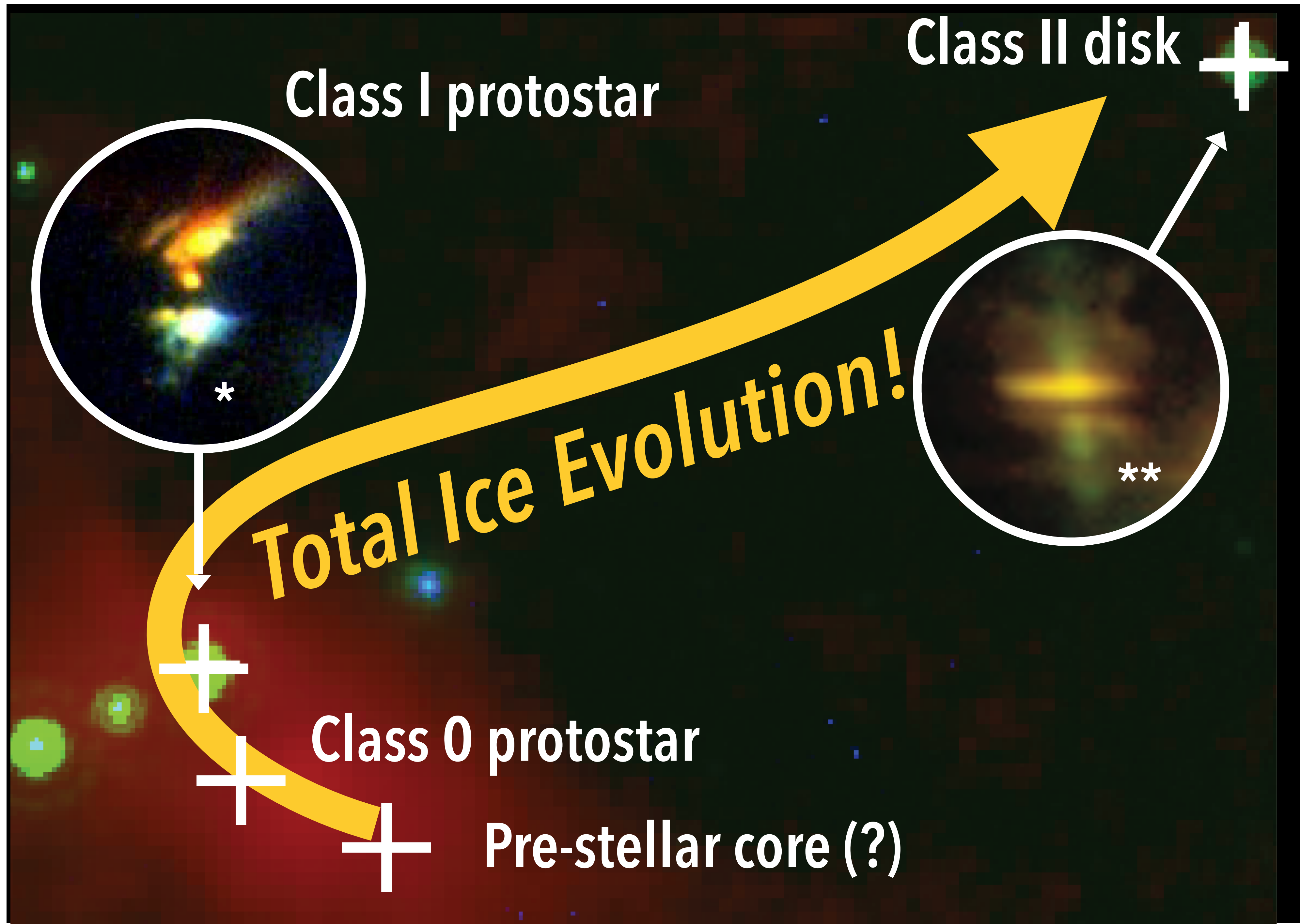
Figure 2: McClure + Ice Age Team (2023)

ENIIGMA: Rocha et al. (2021), Elias 16 (Knez et al. 2005)

Summary and First Conclusions of IceAge

- JWST ERS program Ice Age: First observations of dense cloud ices at $A_V > 50$
  - S/N of ~100-400 at 0.1-10 micro-Jy with relatively short integration times with NIRSpec/MIRI FS.
  - JWST reveals new detections of OCN-, ^{13}C isotopologues, OCS, CH_4, and dOH.
  - Ice profiles reveal <u>grain growth to micron sizes</u> and <u>early chemistry in water-ice</u>.
  - Relative abundances of ices at A_V~60-95 are <u>similar to those at A_V~20</u>…

- More results from Ice Age coming soon…
  - NIRCam survey of background stars behind ChaI.
    - 10s to 100s of lines of sight; L & M band spectra.
  - NIRSpec and MIRI spectroscopy of protostar and disk.



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